REVIEW of the NAVY LINES OF EVIDENCE for GROUNDWATER FLOW: CSM Section 6.8

GROUNDWATER FLOW

First it important to understand that an empirical observation or an initial hypothesis is not a line of evidence. To be accepted, a Line of Evidence (LOE) must have solid supporting data and analysis. This does not seem to be the case for the Navy's LOEs

1) Groundwater levels measured throughout the Facility area of interest are consistent with the regional groundwater levels and flow directions reported in previous studies, which include those by the USGS (Oki 2005) and DON (2007, 2010).
   a) *This is not true. Each of the cited studies showed a mauka to makai gradient of a foot per mile or more going down the ridges. Current data show a very shallow to no gradient going down the Red Hill and Moanalua Ridges.*

2) Spatial distributions of groundwater level elevations measured in the Red Hill area monitoring wells show hydraulic gradients are generally southwestward beneath the Facility, even when Red Hill Shaft was not pumping in November 2016. However, the gradient at Red Hill is extremely gentle and is also affected by local heterogeneities.
   a) *The 18 Nov., 2016 synoptic water level survey shows a weak gradient in the opposite direction of what the Navy is stating in this LOE. Ignoring wells RHMW07 (due the significantly elevated groundwater elevation) and RHMW01 (since RHMW01 is a 1" well with no gyroscopic correction), and HDMW2253-03. Separate regressions done on the tunnel wells and the northwest boundary wells show a gradient of about 5 x 10^{-5} ft/mi dipping up the ridge (that is from OWDF-MW1 toward RHMW04). The November, 2016 synoptic water level survey definitely does not support regional flow down the Red Hill Ridges. Refer to Figure 1.*

3) Quarterly water level data from 2007 to present show that RHMW07 fluctuations closely correspond with other water table monitoring wells and are representative of groundwater levels in the basal aquifer.
   a) *It is generally true that on a quarterly time scale the changes in water level in RHMW07 mimic that of the other wells. It is **NOT** true that the water levels in RHMW07 are representative of the groundwater levels in the basal aquifer. The water level in RHMW07 is about 4 feet higher than that in the surrounding aquifer indicating some sort of compartmentalization of the groundwater in RHMW07 from the main aquifer.*

4) Borehole geologic logs show a deep saprolite zone occurs beneath South Hālawa Valley and forms a low-permeability barrier to groundwater flow. At new monitoring well RHMW11, this saprolite extends to approximately 87 ft below the regional basal groundwater table. New data from multiple intervals in RHMW11 show the saprolite zone is continuously saturated and the groundwater levels in the saprolite are still equilibrating but indicate a downward vertical hydraulic gradient, and the water table is much higher than at the nearby well RHMW07 and other Red Hill wells. However, the lateral and vertical extent of the saprolite has not been delineated particularly in the upper portion of South Hālawa Valley.
   a) *Generally true, but the Navy may be making inferences that are inaccurate or are otherwise not supportable.*
   b) *The saprolite at RHMW11 would only be a barrier to groundwater flow directly across Halawa Valley. There is a significant groundwater elevation difference between the Red Hill area and that*

on the Halawa side of Halawa Valley. To prevent groundwater flow from the Red Hill area to the Halawa side, the saprolite ~~should~~ would need to be present well below the water table for a significant distance up valley from RHMW04. Currently there is no evidence that this condition exists.

c) *The gradient in RHMW11 Z5 to Z1 is generally downward, which could be interpreted as groundwater flowing under the saprolite from Red Hill to Halawa. This would make sense since based on the Navy's interpretation of the seismic data at Transects F and D the sapolite extends less than halfway into the freshwater lens. There is a significant hydraulic head difference between the Red Hill Ridge and Halawa and it would be logical for groundwater to flow beneath the saprolite to the west or northwest.*

5) Groundwater flows from areas of higher recharge to areas lower recharge or discharge. Recharge occurs as a result of direct infiltration of rainfall, seepage from streams and other water sources at the land surface. Recharge rates are spatially distributed throughout the groundwater model area such that higher recharge occurs at higher land surface elevations as recently estimated by the USGS.
   a) *This is a scientifically inaccurate statement. Groundwater flows from areas of higher potential (higher groundwater elevation relative to sea level) to areas of lower potential where hydraulic conductivity is sufficient to allow flow.*

6) Water sources in the Hālawa Quarry/cement plant area north of South Hālawa Valley as well as other local recharge sources may increase groundwater recharge rates locally, create shallow perched water zones, and increase the water table elevation in the basal aquifer in the area north of South Hālawa Valley.

   a) *This is not a line of evidence until supporting data are provided. Right now this is just an untested hypothesis.*
   b) *Section 5.1.4.4 gives the dimensions of the Quarry collection basin as 500 ft by 1,200 ft. Assuming that rainfall in the area is 100 inches per year, this results in about a 100,000 gallons per day infiltration rate. This does seem substantial. However, this is equivalent to a pumping rate of about 70 gpm, which pumping tests show result in minimal changes in the groundwater elevation. So the assertion that focused infiltration results in a significant groundwater mound is very questionable.*

   c) *Due to the brackish wash water used by Quarry, the Navy contends that the salty water in RHMW06 and RHMW07 is evidence of groundwater flow from the north-northwest to Red Hill. The Navy further proposes that the focused recharge from rainfall flowing into the Quarry Pits results in a groundwater mound providing the hydraulic potential for groundwater to flow to the southeast to RHMW06 & 07. In a basalt aquifer it takes a large and persistent recharge flux to result in a groundwater mound. Thus the brackish wash water would be diluted by the fresh rain water. Some quantitative analysis is needed to determine if the recharge into the Quarry is great enough and persistent enough increase the groundwater elevation sufficiently to support groundwater flow to the southeast. It must also be shown that the flux and salinity of this water is great enough to match that in RHMW06 & 07 and has a high enough groundwater elevation to flow into the screen of RHMW07. It is important to note that the saprolite zones on RHMW11 do not show elevated salinity.*

   d) *The brackish water up flowing in the open borehole of HDMW2253-03 is also hypothesized as a source of salinity to RHMW06 and 07. A process must be identified where denser water (due to the increased salinity) from both HDMW2253-03 and the Quarry infiltration can flow through or under the saprolite then rise up into the screens or RHMW06 and 07.*

7) The geologic log of Red Hill Water Development Tunnel (i.e., Red Hill Shaft) shows a highly permeable clinker zone in the last couple hundred feet of the tunnel. Groundwater contours reflect a converging flow pattern toward the eastern end of the water tunnel.

   a) *Partially true but not a line of evidence for groundwater flow patterns.*

8) Time-series water level data from the May 2006 pumping test of Red Hill Shaft and the USGS/BWS May 2015 pumping test of Hālawa Shaft suggest there is a hydraulic barrier located north of monitoring well RHMW07.

   a) *This statement needs more context to judge it validity.*

9) Pump test data from the 2017/2018 synoptic monitoring indicate that RHMW07; RHMW11 Zones 6, 7, and 8; Hālawa Deep Monitoring Well (HDMW2253-03) chase tube and others do not respond to pumping from Red Hill Shaft or Hālawa Shaft.

   a) *A response to pumping at the Red Hill or Halawa Shafts would not be expected in RHMW11 Zones 6, 7, or 8 due to the low permeability of the saprolite.*

   b) *The apparent context of the LOE is unclear, but based on other statements it appears the Navy is contending that RHMW07 is hydraulically connected to the saprolite aquifer and this connection is the reason for the higher groundwater elevation in RHMW07. The Navy further contends that the lack of response of the HDMW2253-03 chase tube and RHMW07 to pumping stresses show the path for groundwater to flow from Red Hill to Halawa is blocked by poorly permeable material.*

      i) *It is true for a direct path for groundwater in the upper part of the aquifer from the facility to Halawa encounters poorly permeable saprolite.*

      ii) *However, this LOE does not consider the possibility of indirect paths from Red Hill to Halawa and that it is the difference in groundwater potential that drives groundwater flow. The presences or absence of a drawdown response is not a LOE for a groundwater flow path.*

      iii) *Pathways for groundwater flow from the Facility to Halawa still exist and are supported by evidence.*

         (1) *The downward gradient at RHMW11 basalt zones implies groundwater flow under the saprolite.*

         (2) *The groundwater elevation at RHMW03 (in the middle of the tank farm) is higher than that in RHMW04, which in turn is much higher than that at the Halawa Shaft even under non-pumping conditions at the Halawa Shaft. So the question becomes: does the saprolite barrier in S. Halawa Valley extend (deeply enough into the water table) far enough up valley to prevent contaminant flow from Red Hill to Halawa? Based on the seismic survey Transect B, the N. Halawa Valley saprolite barrier does not extend far enough up valley to be protective of the Halawa Shaft. Thus the S. Halawa saprolite/valley fill is the only line of defense between the facility and the Halawa Shaft.*

10) Trends in major chemical components in groundwater from monitor wells indicates mixing of two main groundwater types, a sodium-chloride type water from the area north of South Hālawa Valley and sodium-bicarbonate type from the southeast.

   a) *This LOE fails on multiple counts.*

   b) *The Navy contends that one of the sources of sodium-chloride type water is groundwater flowing up the well bore of HDWM2253-03. For this line of evidence to be credible, a process needs to be identified where denser water that enters the aquifer at -100 ft msl rises into the well screens of OWDF-MW1, and RHMW06 & 07 (at elevations of X ft msl ...) after passing through or under the saprolite. (see HDMW2253-03 conductivity-temperature-depth profile, Figure 4).*

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Commented [D1]: I would be a bit reluctant to state this in this way. I would be more comfortable saying that "*...S. Halawa saprolite/valley fill is the only potential physical barrier to direct flow between the facility and Halawa Shaft.*" Another virtual barrier is the distance (and attendant natural attenuation) that protects Halawa Shaft from contamination. Likewise, if we actually understood the subsurface flow lines in the intervening path, those could also provide another virtual barrier...

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c) *Next it is very unclear what the Navy is contenting the source of sodium-bicarbonate type water from the southeast is? The Navy's CSM has the northeast as the major source of fresh water.*

d) *This LOE relies on the mixing implied by the Piper Diagram in Figure 6-31. There appears to be a misunderstanding on the Navy's part on how to interpret Piper Diagrams. While it is true that one of the uses of a Piper Diagram is to assess mixing trends, this assumes conservative mixing. That is, no chemical alteration of the water occurs along the flow path between the end members. The Navy's interpretation of the Piper Diagrams is heavily dependent on the anions. A Piper Diagram considers three anions; bicarbonate, chloride, and sulfate. The proportions of bicarbonate and sulfate are altered due to the natural attenuation processes making anions ~~is~~ an invalid candidate for mixing analysis ~~and~~ since the alteration violates the assumption of conservative mixing.*

e) *It appears that the Navy has chosen RHMW02&03 and OWDFMW-1 as end members. This seems a poor choice since the Navy's mauka to makai CSM would make RHMW04 or RHMW10 the logical upgradient end-members. However, these wells plot in the middle of the hypothesized flow path.*

f) *The Navy rejects the cations due to cation exchange processes. However cation exchange is a process that primarily occurs in more fine grained material and would not be expected to occur to any significant degree over the relatively short travel distances beneath the Red Hill Facility. Since no alteration of cations is expected (unlike anions) along the hypothesized flow path they become much more attractive candidate to evaluate any end-member mixing that may occur. Cations mixing line end-members would become RHMW05&08 and OWDFMW-1. Unfortunately this doesn't really make a sensible flow path either.*

g) *When the Piper Diagram inferred flow and mixing paths are mapped, no logical travel path results (see Figure 2 and 3). From Dever (1997) Appendix I Page 411 "Conversely, if the water compositions do not plot along straight lines in each of the fields their compositions are not controlled by simple mixing." It seems while informative conclusions can come from scrutiny of the Piper Diagrams, groundwater flow paths is not one of them.*

11) Groundwater chemistry data from Red Hill area wells compiled and evaluated by UHM, which include major ions and stable isotopes of oxygen and hydrogen, support the conceptual model of the groundwater recharge and flow pattern in the Red Hill Facility area described above.

a) *It would be interesting if the Navy were to consult with the UH scientist that provided that data. Likely they would disagree with this assessment. Also see some of the comments in #`10.*

b) *One of the over-riding themes that UHM stressed when delivering the geochem data to the Navy was the great chemical variability within the Red Hill Groundwater Monitoring Network. The variability was as great or in some cases greater than that in USGS 2004 NAWQA Study, which sampled all of central Oahu and the Honolulu Aquifer. It was further suggested that this variability indicated a degree of compartmentalization of the groundwater. The Navy's CSM states that groundwater beneath the facility originates in the high elevation recharge areas and flows directly downslope through the facility to coastal and discharge zones. This mauka to makai flow is augmented by upflow through HDMW2253-03 and focused recharge at the Quarry significantly altering the chemistry of wells along the northwest Red Hill Facility boundary. With the exception of RHMW04, the chloride concentrations in the northwest boundary wells is an order of magnitude greater than that in upper tunnel wells (RHMW02 & 03). The Navy's CSM requires a significant flux of groundwater from HDMW2253-03 and the Quarry to account for the salinity in the northwest boundary wells. The Navy's CSM also fails to account for the increase in salinity going from the northeast to the southwest. Thus Number 11 Line of Evidence really does need more substantial justification before it can be considered valid.*

c) *The wide variability in groundwater chemistry and the flat gradient could be more easily explained by much less groundwater flowing beneath the Red Hill Facility. Much lower inputs of chemically contrasting groundwater would be required to attain the span of chemistry we observe. Regarding the elevated salinity in RHMW06&07, it is interesting to note that in the 2000 investigation of the Oily Waste Disposal Basin a groundwater flow direction was measured from OWDB wells toward RHMW06&07 (see Figure 5). High salinity was measured in two out of three basal wells installed in the OWDB providing a source of salts to RHMW07 & 06. It seems this flow path is easier to reconcile with the available data than that proposed by the Navy.*

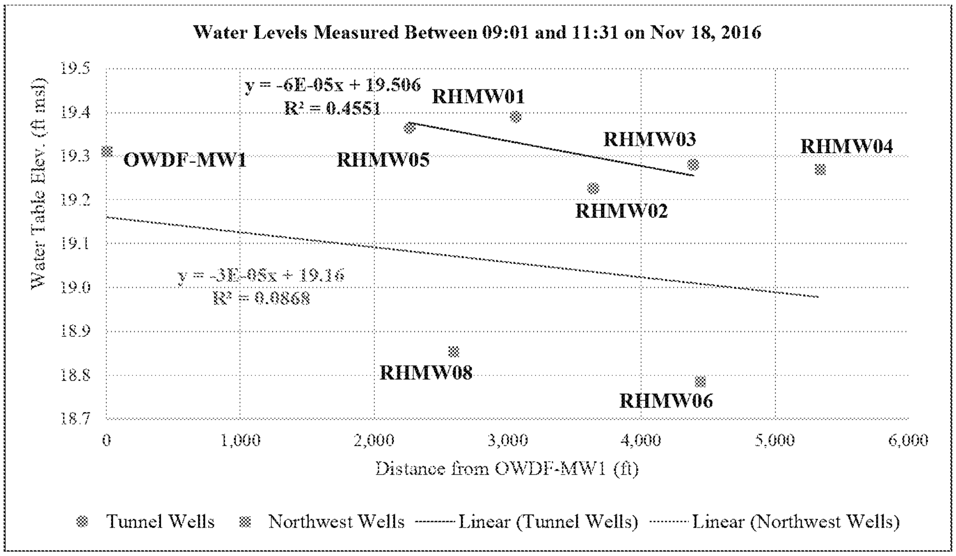

Figure 1. Data from the Nov. 18, 2016 synoptic water level survey showing the groundwater elevation in the Red Hill Monitoring Wells versus distance up the Red Hill Ridge from OWDF-MW1. Trends for both the tunnel wells and the northwest boundary wells (excluding RHMW07) do not support groundwater flow down the Red Hill Ridge when the Red Hill Shaft is not pumping.

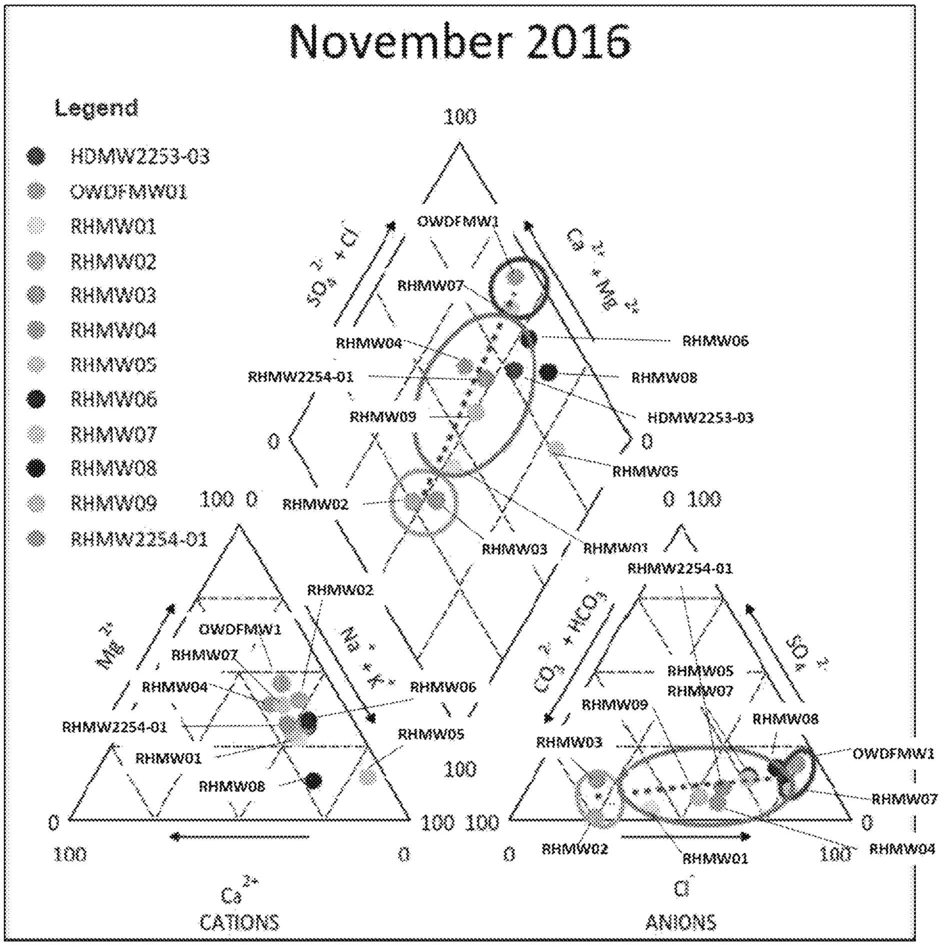

Figure 2. The proportional chemical distribution of the major dissolved ions as reported by AECOM at the November SME meeting. The Navy is contending that the Piper Diagrams show that groundwater is flowing from RHMW02&03 to OWDF-MW1.

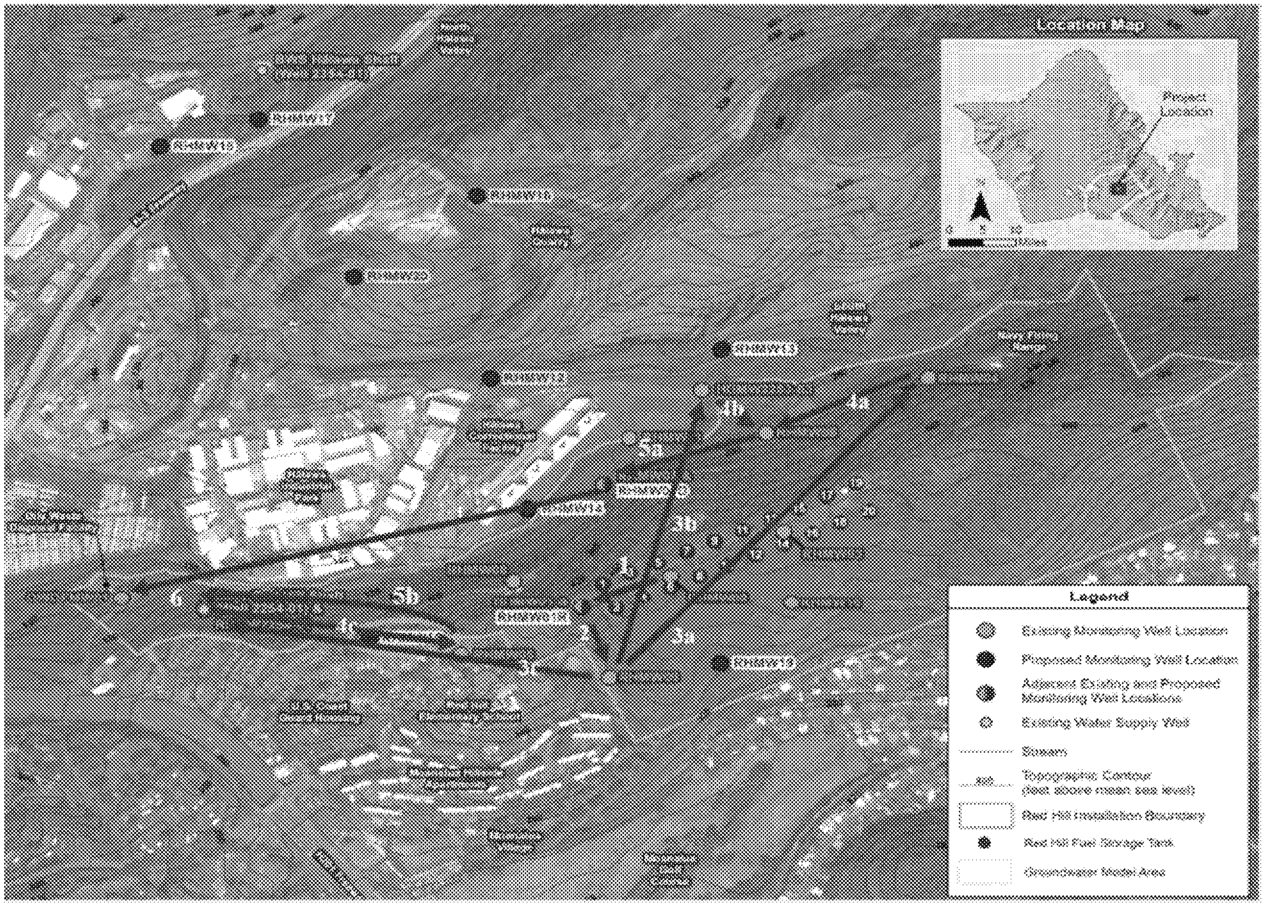

Figure 3. The map above shows the directions and sequence of groundwater flow between wells as implied by the Piper Diagram in Figure 2. Take home point is that no coherent flow path can be deduced from the Piper Diagrams.

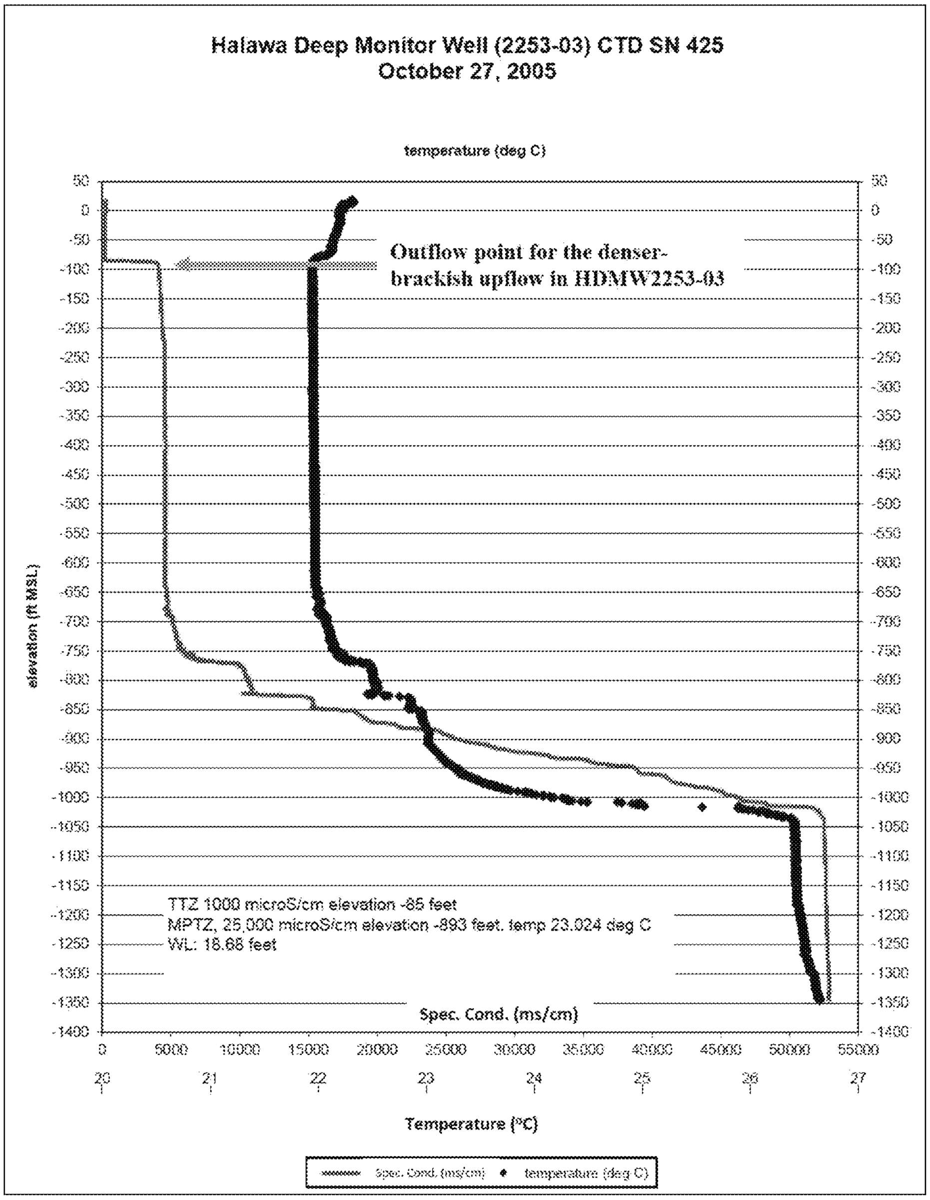

Figure 4. The Conductivity-Temperature-Depth profile of the HDMW2254-03 Well shows that the denser-brackish water flows up from -700 ft msl within the well bore then exits at -100 ft msl, significantly below the elevations of the RHMW06&07 well screens.

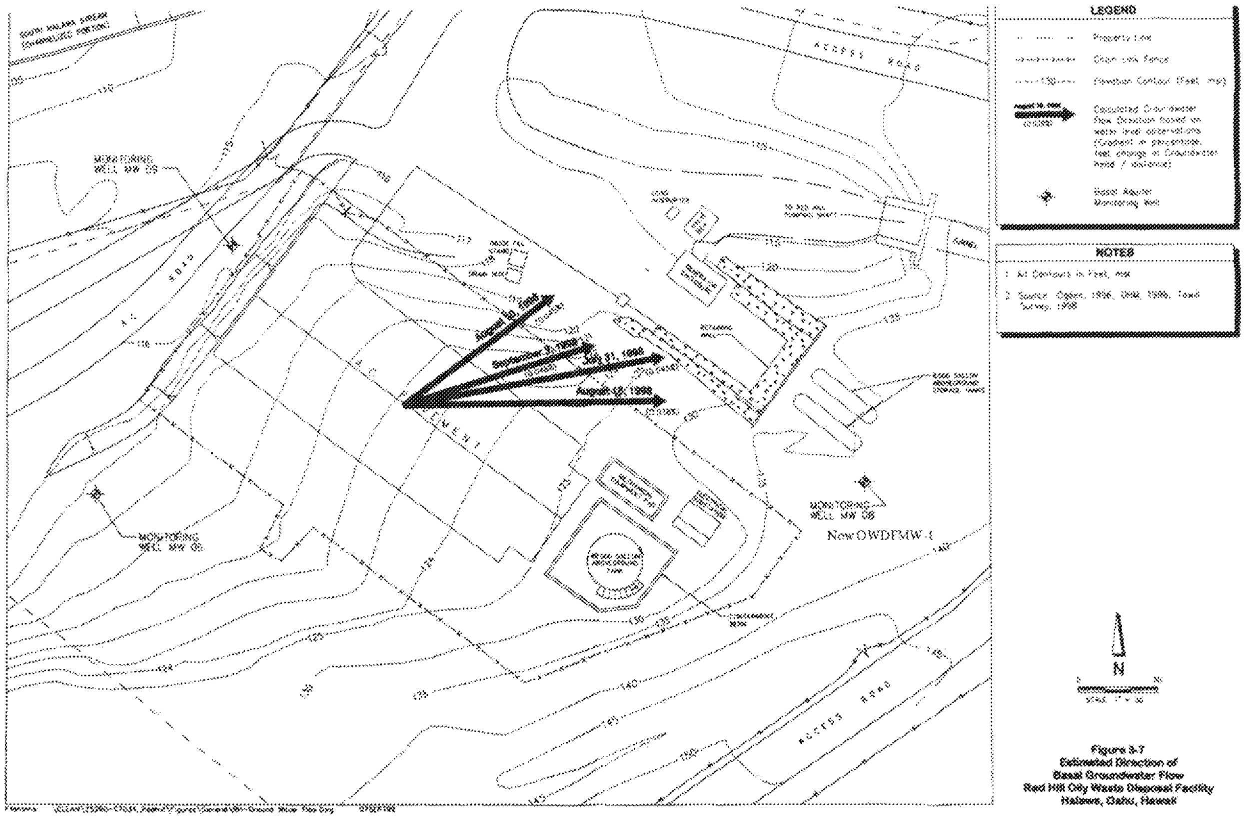

Figure 5. Testing at the Oily Waste Disposal Basin indicated that groundwater from the OWDB goes in a direction more towards RHMW07&06 rather than in the logical direction towards the Red Hill Shaft. The direction to the Red Hill Shaft would be about 105°, while the direction to RHMW07 would be about 080-085°.